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Surface and Subsurface Tillage Effects on Mine Soil Properties and Vegetative Response

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Soil compaction is an important concern for surface mine operations that require heavy equipment for land reclamation. Excessive use of rubber-tired equipment, such as scraper pans, may cause mine soil compaction and hinder the success of revegetation efforts. However, information is limited on management strategies for ameliorating the potential compacting effects of scraper pans, particularly during site preparation for loblolly pine (*Pinus taeda* L.) plantations. Three forms of tillage and one control were replicated five times on surface mined land in the west Gulf Coastal Plain: no tillage (NT), disking (D), single-ripping + disking (R+D), and cross-ripping + disking (CR+D). Mine soil physical properties were investigated at 0 to 30, 30 to 60, and 60 to 90 cm. Percent cover and aboveground biomass of an herbaceous winter cover crop, and survival and growth of loblolly pine seedlings were assessed after one growing season. Herbaceous species biomass was highest on the R+D and CR+D plots and lowest on the NT control. Pine seedling survival was highest on the tilled plots (>90%) compared to NT (85%). The highest intensity combination tillage treatment (CR+D) was superior in terms of lowering soil bulk density (mean 1.36 Mg m^{-3}) and soil strength (mean 2220 kPa) and increasing pine seedling volume index growth (mean 32 cm^3). Surface tillage (D) alone improved herbaceous cover and pine seedling survival, while CR+D provided the most favorable responses in mine soil physical properties and vegetative growth.

Abbreviations: AWC, available water capacity; CR+D, cross-ripping plus disking; D, disking; FC, field capacity; NT, no tillage; R+D, single-ripping plus disking; SVI, seedling volume index; WC, wilting coefficient.

During reclamation of surface-mined land, the procedures used in establishing a plant growth medium, or mine soil, can influence soil properties and revegetation success both short and long-term (Zipper et al., 2013). If improper mine soil handling and placement results in compaction, adverse growing conditions may arise, including elevated soil bulk density and reduced rainfall infiltration, available water capacity, aeration, and plant nutrient availability (Slick and Curtis, 1985). Mined land reclamation offers an opportunity to improve soil properties through mechanical site preparation to achieve the post-mining land use goal (Skousen et al., 2009). Forestry is a common post-mining land use in the Gulf Coastal Plain, with the majority of land reclaimed to commercially valuable loblolly pine (*Pinus taeda* L.) plantations (Priest et al., 2016). Since mine operations require year-round use of heavy, earth-moving equipment, a limiting factor for vegetative growth and establishment on mined land is soil compaction, which can have long-lasting consequences if not minimized or ameliorated prior to planting (Dunker and Darmody, 2005). Compaction alters the size, arrangement,

Core Ideas

- **Mine soil physical properties improve with increased tillage upon reclamation in the Gulf Coastal Plain.**
- **Growth of loblolly pine seedlings increases with higher intensity tillage on reclaimed mined land.**
- **Aboveground herbaceous cover and biomass increases with tillage on reclaimed mined land.**

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and distribution of soil pores, which influences air, water, and gas movement in the soil, and thus, biological activity and root growth (Sutton, 1991).

Mitigating the negative effects of soil compaction on plant growth is crucial in building proper management strategies for a particular land use. The Surface Mining Control and Reclamation Act (SMCRA) requires that surface mine operations reclaim land to a capability that is equal to or greater than the pre-mining land use (SMCRA, 1977). Soil tillage temporarily loosens soils, which in turn encourages the exploration of plant roots into increased soil volume (Morris and Lowery, 1988). Disking, or disk harrowing, bedding, chisel plowing, subsoiling, and combination plowing are a few examples of conventional tillage techniques (Miller et al., 2004). Since the 1950s, mechanical site preparation has aided in southern pine plantation establishment on non-mined land (Fox et al., 2007; Morris et al., 2006). Operational surface disking has been shown to improve loblolly pine seedling growth and in some cases, provided a greater response compared to higher intensity treatments (Carlson et al., 2006; Lincoln et al., 2007). Combination plowing (surface + subsurface tillage) prior to planting in the southeastern United States has been shown to improve the survival and growth of loblolly pine compared to no-tilled treatments (Carlson et al., 2014; Wheeler et al., 2002).

Despite the previous work outlined above, the effects of similar mechanical site preparation techniques for loblolly pine plantations growing on reclaimed mined land have yet to be studied. Furthermore, the reclamation methodology commonly used in the Gulf Coastal Plain includes the use of tractor-pulled scraper pans. Studies have shown that scraper placed mine soil results in poorer soil physical properties and lower yield responses compared to other reclamation methods (Dunker and Darmody, 2005; Hooks et al., 1992; McSweeney and Jansen, 1984). One knowledge gap in the current literature is determining the best mechanical site preparation strategy for reforesting loblolly pine on scraper placed mine soil. While surface disking is a common practice on reclaimed mined land in the Gulf Coastal Plain, the effects of surface versus subsurface tillage on reclamation success have not been studied.

Subsurface tillage, or deep ripping, was first introduced on reclaimed prime farmland in the Midwest to increase yield production after the implementation of the Surface Mining Control and Reclamation Act (Sweigard et al., 2007). The USDA advises deep ripping with a dozer when mine soils are prepared using rubber-tired equipment such as scraper pans (USDA Forest Service, 1979). There are various applications of dozer ripping, such as single ripping in one direction or cross-ripping in a grid pattern. Significant short-term growth improvements have been made for trees growing in the Appalachian coal fields by ripping previously compacted mined land (Bauman et al., 2014; Burger and Evans, 2010). Casselman et al. (2006) found that yellow-poplar (*Liriodendron tulipifera* L.) seedlings yielded significantly higher growth and total biomass in dozer ripped soils. Additionally, prime farmland crops growing on a scraper placed mine soil increased yields when the depth of tillage increased from 23 to 122 cm (Dunker et al., 1995). Results were attributed in part to lower soil strength.

The majority of tillage studies on reclaimed mined land have been conducted on prime farmland in the Midwest and post-bond release reclaimed mined land in Appalachia (Dunker and Darmody, 2005; Zipper et al., 2011). Given that mined lands vary by region, site conditions, and post-mining land use, there is a need to quantify the effects of different tillage techniques on mine soil properties and vegetative response following current reclamation methodologies in the Gulf Coastal Plain. Improved understanding of these influences will ultimately help inform management decisions regarding mined land reclamation and loblolly pine reforestation. The objective of this study was to examine the impact of various soil tillage techniques on scraper placed mine soil at an operational lignite coal surface mine by evaluating the responses of soil physical properties, herbaceous species, and loblolly pine seedlings.

MATERIALS AND METHODS

Study Area

The study site was located at the Oak Hill Mine in Rusk County, Texas (32°12′50.007″ N, 94°43′57.6942″ W) (Fig. 1), which is owned by the Luminant Mining Company, LLC. This location was chosen due to the recently reclaimed condition of the study area and because it would be prepared to support loblolly pine plantations as the post-mining land use in a similar way to other mine sites common to this region. The Oak Hill Mine was one of three active lignite coal surface mine operations supporting the Martin Lake Power Plant in eastern Texas. Rusk County averages 1255 mm of rainfall annually with an average high temperature of 24°C and an average annual temperature of 18°C (NOAA, 2016a). Throughout the data collection year in 2016, rainfall totaled 1346-mm. The highest amount of rainfall occurred in April, August, and March, respectively (NOAA, 2016b). Once surface mining is complete, the approximate

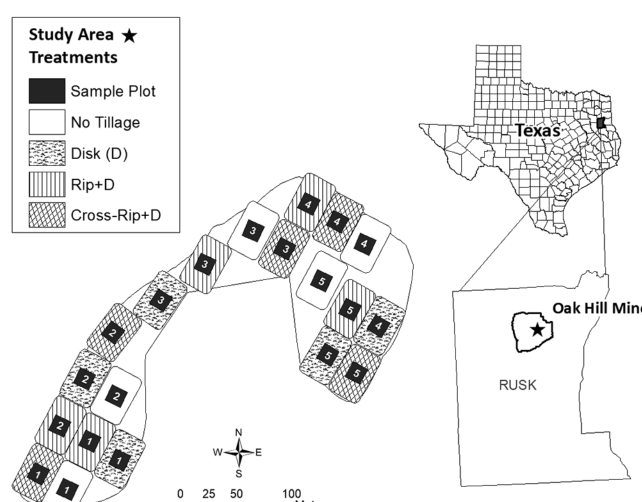

Fig. 1. Location and experimental design of the study area at the Oak Hill Mine in Rusk County, Texas. Block numbers are shown on sample plots (5 blocks × 4 treatments = 20 replicate plots).

original contour is reclaimed by returning and smoothly grading the overburden, or overlying earthen and rock materials. At the Oak Hill Mine, tractor pulled scraper pans are typically used to transport and place, using multiple passes, the final veneer layer of mine soil to serve as the plant growth medium. Texas mining companies are required by state regulatory authority to replace at least 1.2 m of growth medium (Railroad Commission of Texas, 1982). The mine soil is derived from newly salvaged or previously stored oxidized surface materials removed prior to mining. Dominant pre-mining soils by land area comprising the Oak Hill Mine are the Cuthbert (fine, mixed, semiactive, thermic Typic Hapludults), Redsprings (fine, kaolinitic, thermic Ultic Hapludalfs), and Tenaha (loamy, siliceous, semiactive, thermic Arenic Hapludults) soil series (Griffith, 2000).

Experimental Design

A randomized complete block design was used to test the effects of varying levels of soil tillage and to account for a topographic gradient. Three tillage techniques and one control treatment were installed in August 2015 during relatively dry conditions at a site recently reclaimed by scraper pans (Fig. 2). Treatment plots were approximately 21 m by 38 m (20 total). One measurement plot (15 m by 15 m) occurred in the middle of each treatment plot (Fig. 1). Treatments were: no tillage (NT), disking (D), single-ripping + disking (R+D), and cross-ripping + disking (CR+D). For purposes of this study, soil depth was defined as 0 to 30 cm for the surface and >30 cm for the subsurface. Surface tillage (D) was installed with one pass of a tractor pulled Rome disk harrow with 16 blades to a depth of approximately 30 to 35 cm. Subsurface tillage (R+D and CR+D) was installed using a Caterpillar D-8 bulldozer with one mounted ripping shank (90 cm). Single-ripping was installed with one single dozer pass on 2-m centers. For cross-ripping, the bulldozer made additional single passes perpendicular to the preexisting single rips (90 cm depth) on a 2-m grid pattern. Ripped plots were then surface disked as described above. All subsequent site preparation treatments were applied to all plots uniformly according to Luminant Mining Company's normal operating procedures for pine tree planting, including seeding of an herbaceous winter cover crop. In November 2015, one final disking treatment (15 cm depth) was applied on all treatment plots except the control. The study site was then uniformly broadcast with a mix of winter wheat (*Triticum* spp.) and 17–17–17 pelletized fertilizer at 140 kg ha^{-1}, and then roller packed with a Brillion seeder, applying crimson clover (*Trifolium incarnatum*) at 30 kg ha^{-1}. In January 2016, 1-0 bare root loblolly pine seedlings were machine planted on a 2.1 m by 3.0 m spacing. Seedlings were planted across the site without regard to the previously ripped furrows, which were no longer discernable due to subsequent surface tillage.

Soil Sampling

The methods used during soil field sampling and laboratory analyses were based on Methods of Soil Analysis (Klute, 1986). Forty soil test pits (2 pits × 4 treatments × 5 reps) were dug at the site with a trackhoe. Each pit was approximately 1.22 m by 1.22 m by 1.07 m. In July 2016, measurements were taken on an undisturbed pit face at 15-, 45-, and 75 cm to represent the midpoints of the three main sampling depths: 0 to 30, 30 to 60, and 60 to 90 cm. A sharp shooter spade was used to shave off ~5 cm of soil before sampling, which occurred at the middle of the pit's sides to reduce edge effects from the trackhoe. Using the slide hammer method, a set of four soil cores were extracted at each sampling depth. Mean values for soil bulk density (ρ_b), volumetric water content (θ), total porosity, field capacity (FC), wilting coefficient (WC), and available water capacity (AWC) were determined from the two middle soil cores to reduce edge effects from the slide hammer. The remaining two outer soil cores were composited by depth and used as samples for the texture analysis. Gravimetric water content was

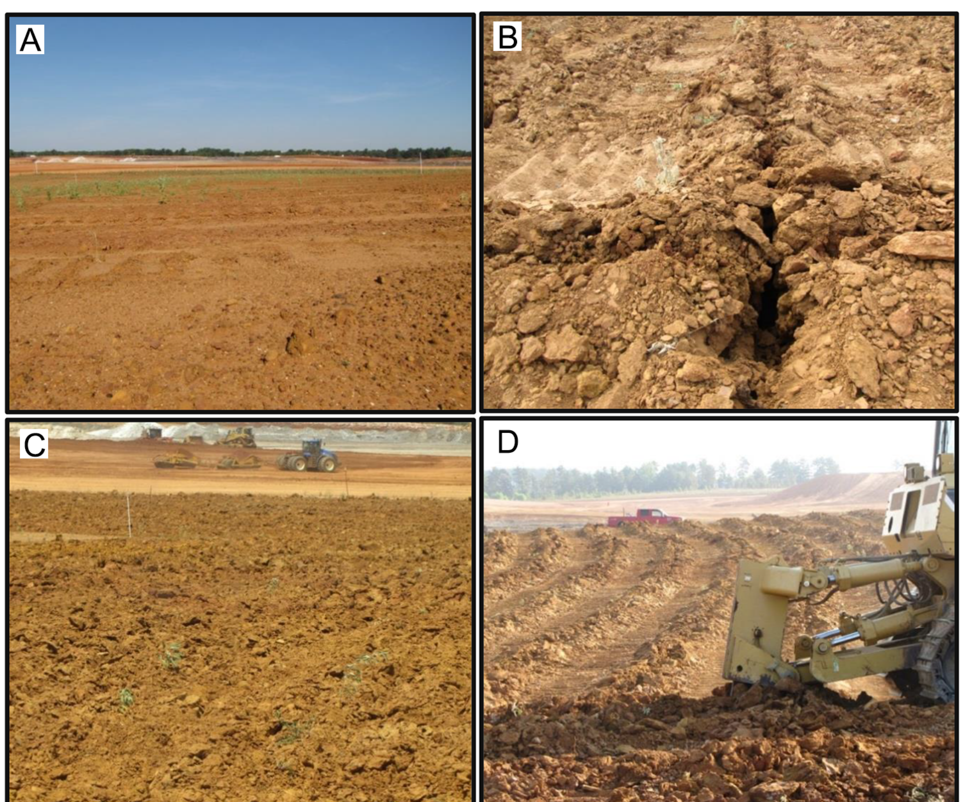

Fig. 2. Treatment installation (August 2015). (A) no tillage; (B) single-ripping plus disking (90 cm on 2-m centers); (C) disking (30 to 35 cm); (D) cross-ripping plus disking (90 cm on 2-m grid pattern). One additional disking pass was applied on ripped plots immediately following dozer ripping.

measured at the soil surface (0 to 30 cm) in March 2016 and later converted to a volume basis using average ρ_b from corresponding sample locations. Soil strength was measured using a FieldScout electronic cone penetrometer equipped with a 30° cone and 1.3-cm diameter tip (SC 900 Soil Compaction Meter, Spectrum Technologies, Inc., Aurora, IL). Two penetrometer readings were recorded at 10-cm intervals to a depth of 90 cm and averaged to one value per depth interval. A double-ring cylinder infiltrometer was used to determine saturated hydraulic conductivity (K_s) (IN8-W Turf Tec International Model, Tallahassee, FL) (ASTM, 2009). The inner and outer cylindrical rings had a diameter of 15 and 30 cm, respectively, with a height of 18 cm. A steel driving plate was used to insert the infiltrometer ~5 cm into the ground twice per measurement plot (IN6-W Turf Tec International Model, Tallahassee, FL).

Vegetative Sampling

Aboveground herbaceous biomass production was collected at three randomly located sample points per measurement plot for a total of 60 samples. Vegetation was cut within a 1 m by 1 m quadrat at the soil surface using grass clippers. Samples were transferred to the lab and oven-dried at 60°C to constant weight. Percent cover of the winter cover crop was visually estimated using six cover class ranges (Daubenmire, 1959): (1) 0 to 5%; (2) 5 to 25%; (3) 25 to 50%; (4) 50 to 75%; (5) 75 to 95%; and (6) 95 to 100%. Tree planting rows were used as transects, serving as the sampling units. Height and ground-line diameter of loblolly pine seedlings were measured immediately after tree planting on approximately 42 trees per subplot (15 m by 15 m). Tree seedling volume index (SVI), the product of squared ground-line diameter and height, was determined in January 2016 and after one growing season in October 2016. Initial SVI was used to determine the relative growth of tree seedlings after one growing season. Survival was recorded during growth measurements. Thirty pine seedlings were randomly selected from the planting stock and placed in cold storage. Seedlings were separated by biomass component (i.e., needles, stems + branches, and roots), measured for aboveground height and diameter, and oven-dried at 60°C to constant weight. Seedling roots were rinsed over a wire screen to catch broken roots. The same procedure was used for harvested seedlings. The following model (Priest et al., 2015) was used to predict above and belowground biomass of all planted seedlings after one growing season:

$$Y = \beta_0 \times (GLD^{\beta_1}) \times (HT^{\beta_2})$$

where Y is the dry weight biomass component (g); GLD is the ground line diameter (mm); HT is the seedling stem height (mm); and β_0, β_1, and β_2 are the regression parameters to be estimated. The predictor variables were seedling height and ground-line diameter. Response variables included needle, stem, root, aboveground and total tree biomass components. In November 2016, four pine seedlings were randomly chosen per treatment plot and harvested in the field at the root collar to determine aboveground biomass. OF the four harvested tree seedlings, one was selected at random for belowground harvesting. Due to a lack of larger seedlings randomly selected for belowground harvest, additional seedlings were harvested in February 2017. The protocol included harvesting the largest tree in each treatment (four trees total) in a randomly selected block to extend the range of interpolation for the total tree and root biomass models. Using shovels, pits were excavated with a diameter equal to the sample seedling height and depth following the taproot.

Table 1. Mean (standard error) soil texture by depth across treatments for 0- to 30-, 30- to 60-, and 60- to 90-cm depths at a surface mine in east Texas.

Depth	Sand	Silt	Clay	Texture
cm		%		
0–30	60 (1.1) a†	12 (1.0)	28 (0.9) b	Sandy clay loam
30–60	56 (0.8) ab	11 (0.7)	33 (0.8) a	Sandy clay loam
60–90	53 (2.2) b	14 (2.1)	33 (1.2) a	Sandy clay loam

† Means within columns followed by the same letter are not different ($\alpha = 0.10$).

Statistical Analyses

All analyses were performed in SAS v.9.2 (SAS Institute, 2008) using PROC MIXED for a two-way factorial ANOVA. Assumptions of normality and homogeneity of variance were verified using PROC UNIVARIATE and a Levene's test, respectively. PROC GLIMMIX was used to assess tree survival. Analysis of covariance was used to determine effects of soil strength using θ as a covariate. Least squares means were calculated for variables with significant differences. An α level of 0.10 was used due to the operational nature of this study; however, p-values in the range of 0.05 to 0.10 were interpreted as showing a general trend toward significance. Nonlinear regression was used to create the allometric relationships for predicting pine seedling above and belowground biomass, using PROC NLIN to estimate regression coefficients.

RESULTS

Soil Response to Tillage

The mix of oxidized materials resulted in a generally consistent sandy clay loam soil texture across the study site with an increase in clay content at subsurface depths ($p = 0.0013$) (Table 1). Interaction effects between tillage treatment and depth for all soil parameters were not significant ($p > 0.10$) (Table 2). Soil physical properties that produced the greatest response from treatments were ρ_b and soil strength (Table 3). Soil ρ_b ranged from 1.36 to 1.55 Mg m^{-3} on CR+D and NT plots,

Table 2. P-values for tillage treatment, soil depth, and fixed effects interactions of soil physical properties at a surface mine in east Texas ($\alpha = 0.10$).

Effect	Bulk density	Soil strength	Total porosity	Field capacity	WC†	AWC†	VWC†	K_s†
Tillage (T)	<0.0001	<0.0001	0.0031	0.4703	0.1251	0.7603	0.0789	0.5569
Depth (D)	0.0833	<0.0001	0.5946	0.0128	0.0196	0.0551	<0.0001	–
T × D	0.8932	0.9850	0.8442	0.7838	0.7880	0.9764	0.3476	–

† WC, wilting coefficient; AWC, available water capacity; VWC, volumetric water content; K_s, saturated hydraulic conductivity.

Table 3. Mean (standard error) soil physical properties by treatment and sampling depth at a surface mine in east Texas.

Treatment†	Bulk density	Total porosity	Volumetric water content	Field capacity	Wilting coefficient	Available water capacity	Saturated hydraulic conductivity‡
	$Mg\ m^{-3}$	%	——	——	$m^3\ m^{-3}$	——	$cm\ h^{-1}$
NT	1.55 (0.02) a§	43 (1.00) a	0.28 (0.01) c	0.33 (0.01)	0.18 (0.01)	0.16 (0.01)	1.76 (0.46)
D	1.44 (0.03) b	45 (1.15) ab	0.27 (0.02) bc	0.33 (0.01)	0.17 (0.01)	0.16 (0.01)	2.31 (0.88)
R+D	1.43 (0.02) b	46 (1.19) b	0.25 (0.01) ab	0.33 (0.01)	0.16 (0.01)	0.17 (0.01)	2.12 (0.60)
CR+D	1.36 (0.03) c	49 (1.16) c	0.24 (0.01) a	0.31 (0.01)	0.16 (0.01)	0.15 (0.01)	2.34 (0.62)
Depth							
cm							
0–30	1.41 (0.03) b	47 (1.20)	0.20 (0.01) a	0.30 (0.01) a	0.16 (0.01) b	0.14 (0.01) a	–
30–60	1.44 (0.03) ab	46 (1.09)	0.27 (0.01) b	0.33 (0.01) b	0.18 (0.01) a	0.15 (0.01) a	–
60–90	1.48 (0.02) a	45 (0.74)	0.31 (0.01) c	0.34 (0.01) b	0.17 (0.00) b	0.18 (0.01) b	–

† NT, no tillage; D, disking; R+D, single-ripping plus disking; CR+D, cross-ripping plus disking.

‡ Saturated hydraulic conductivity was measured at the surface only.

§ Means within columns followed by the same letter are not different (α = 0.10).

respectively ($p < 0.0001$), and ρ_b values had a tendency to increase with soil depth across all treatments ($p = 0.0833$). Vertical soil strength was measured in March 2016 within and between planted tree rows. When adjusted for variability in water content ($p = 0.0070$), soil strength between tree rows decreased with increasing tillage intensity ($p = 0.0497$) (Fig. 3). The θ between tree rows showed no treatment effects, ranging from 0.25 to 0.32 $m^3\ m^{-3}$ ($p = 0.8962$). Soil strength within tree rows followed a decreasing trend with increasing tillage intensity ($p = 0.0840$) and there were no accompanying water content measurements taken for these data. Horizontal soil strength, which was measured in July 2016, decreased with increasing tillage intensity ($p < 0.0001$) and varied by depth ($p < 0.0001$) (Fig. 3). Highest soil strength occurred at 20 to 60 cm, whereas lowest soil strength occurred at 70 to 90 cm. Soil strength showed lower values during the summer season, though penetrometer readings were measured horizontally by depth and are not directly comparable to the spring season data. Total porosity was significant and varied by 6% between the two treatment extremes, NT and CR+D, following an inverse trend to that of ρ_b ($p = 0.0031$). Soil K_s was not significant across tillage treatments ($p = 0.5569$) (Table 3). Soil θ increased with depth ($p < 0.0001$) and varied between treatments ($p = 0.0789$) (Table 3). Compared with NT, θ showed a decreasing trend on CR+D, while D and R+D treatments had intermediate effects on θ. The highest θ occurred at 60 to 90 cm (0.31 $m^3\ m^{-3}$). Increases in FC ($p = 0.0128$) and WC ($p = 0.0196$) with soil depth were ob-

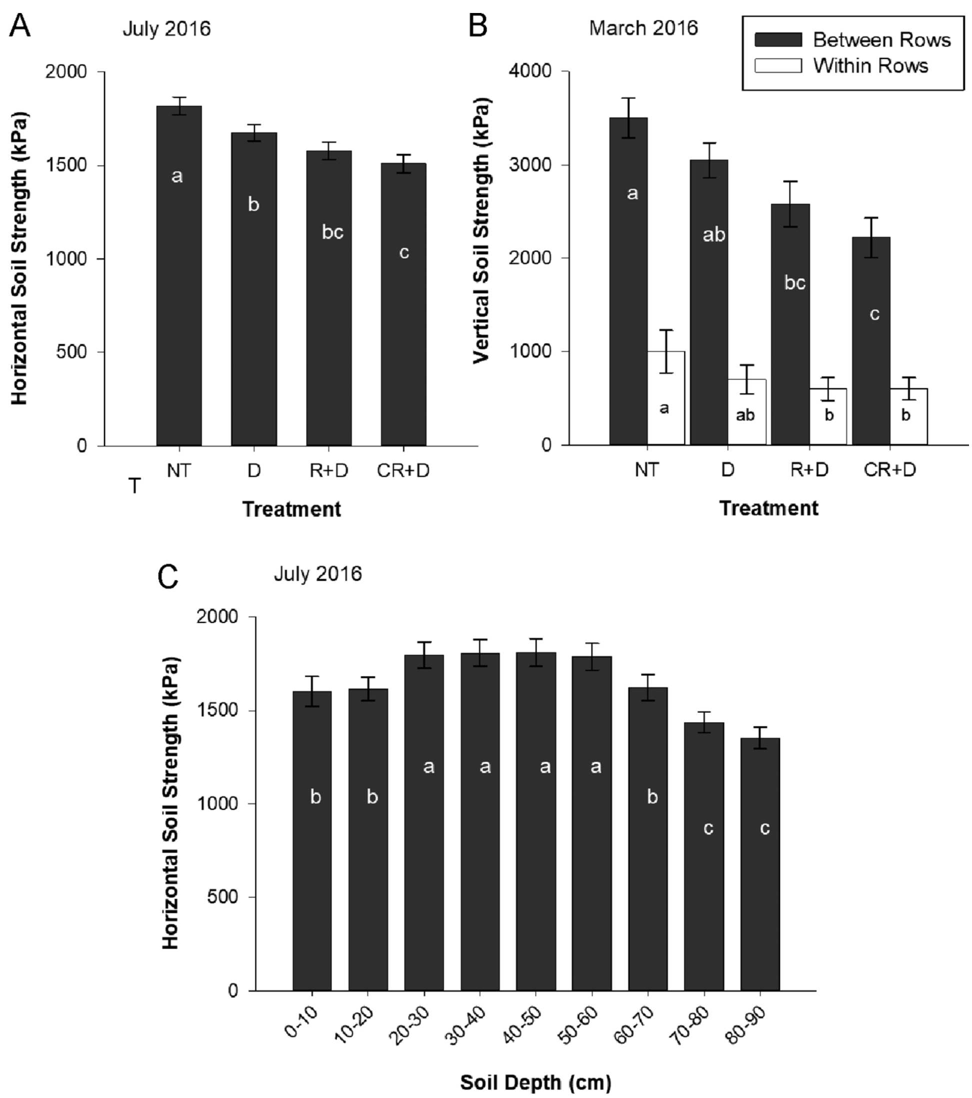

Fig. 3. Mean soil strength with standard error bars by treatment or depth in March and July 2016 at a surface mine in east Texas. Shared letters are not different (α = 0.10).

served (Table 3); however, in each case the magnitude of these differences was relatively small. Soil AWC showed an increasing trend with soil depth ($p = 0.0551$).

Vegetative Response to Tillage

Loblolly pine seedling survival ranged from 85 to 97% during the first growing season with highest survival on R+D and CR+D plots ($p < 0.0001$) (Table 4). Feral hog browse occurred on some pine seedlings across the site; however, impacts on survival were minimal. Pine seedlings growing on CR+D plots had taller height, wider ground-line diameter, and greater SVI after one growing season compared to other treatments (Table 4). The NT and R+D plots exhibited similar ground-line diameter ($p = 0.8814$) and SVI ($p = 0.5593$). Seedling height was similar for D and R+D ($p = 0.1663$), and for D and NT ($p = 0.5997$). Smallest seedlings in terms of ground-line diameter and SVI were on D plots. Cover of herbaceous species was significantly greater on tilled plots ($p = 0.0003$) (Table 5). Overall, NT had the lowest cover (54%). Aboveground biomass production of the herbaceous species after one growing season (November to May) ranged from 1.0 to 3.0 Mg ha^{-1} on NT and CR+D plots, respectively ($p = 0.0102$) (Table 5). Seedling biomass production for stem, root, aboveground, and total tree components was highest on CR+D compared to other treatments (Table 5). Stem biomass was significantly lower on D plots. No differences existed in root biomass between NT, D, and R+D ($p > 0.10$). The NT plots ranked second highest in aboveground biomass production and exhibited no differences in needle biomass compared to CR+D (Table 5).

Table 4. Mean (standard error) pine seedling survival and growth with standard errors after one growing season at a surface mine in east Texas.

Treatment†	Survival	Height growth	Diameter growth	Volume index growth
	%	——— cm ———		cm^3
NT	85 (3.0) a‡	17 (0.6) a	0.26 (0.01) b	19 (1.1) b
D	91 (2.0) b	17 (0.5) ab	0.18 (0.01) a	14 (0.8) a
R+D	95 (2.0) bc	18 (0.6) b	0.25 (0.01) b	18 (1.1) b
CR+D	97 (1.0) c	30 (0.6) c	0.35 (0.02) c	32 (2.7) c

† NT, no tillage; D, disking; R+D, single-ripping plus disking; CR+D, cross-ripping plus disking.

‡ Means within columns followed by the same letter are not different ($\alpha = 0.10$).

DISCUSSION

Surface disking alone was inferior in terms of alleviating compaction to a level that improved early tree growth at this mine site. However, lower tree survival and herbaceous cover on NT showed that disking was beneficial to vegetative establishment. Lower cover on NT may have been a product of either poor germination of the seed or increased mortality post germination as a result of higher soil compaction. Based on personal communication with the operator, machine tree planting on NT was more difficult, likely due to the higher soil compaction described above. Consequently, there were several instances of shallow planting (poor soil-to-root contact), which may have contributed to lower survival. Survival of tree seedlings across all treatments exceeded the average pine stocking standard (182 live trees ha^{-1}) for mined land in Texas (Railroad Commission of Texas, 1990). High survival may have been partly due to the greater than average amount of rainfall for Rusk County, Texas in 2016 (1346 mm in 2016 compared to the 1255-mm average). The combination of subsurface cross-ripping and surface disking improved soil physical properties at this mine site, which likely increased the ability of tree roots to exploit a greater soil volume, thereby promoting resource availability beyond what lower intensity treatments offered.

We were not able to precisely determine which soil physical properties translated into improved growth due to the operational nature of this study. Vegetative response was probably based on several soil-related factors. Furtado et al. (2016) found positive responses in tree seedling size based on operational tillage treatments; however, they were not able to accurately predict growth from average soil strength measurements, which are highly variable based on soil water regimes, soil physical properties, and site conditions. Conversely, Thompson et al. (1987) found that both soil strength and ρ_b were highly correlated to root length density in the lower rooting zone for a corn row cropping system. However, they found that ρ_b was slightly more accurate in this prediction. Soil texture across the study site was sandy clay loam (Table 1), so it is unlikely that minor textural differences impacted observed treatment effects for vegetative growth.

The increase in clay at subsurface depths may have been partly responsible for the depth effects and trends therein associ-

Table 5. Mean (standard error) predicted biomass production with standard errors for pine seedlings and herbaceous species after one growing season at a surface mine in east Texas.

Treatment†	Pine seedlings					Herbaceous species	
	Needles	Stem	Roots	Aboveground	Total tree‡	Cover	Aboveground
	——— g ———					%	Mg ha^{-1}
NT	8.9 (0.5) b§	5.11 (0.1) b	6.0 (0.4) a	14.1 (0.6) b	22.3 (1.1) a	54 (3.6) a	1.03 (0.16) a
D	5.5 (0.3) a	3.5 (0.1) a	7.2 (0.5) a	9.3 (0.4) a	21.6 (1.2) a	86 (2.1) b	1.64 (0.20) ab
R+D	5.7 (0.3) a	4.8 (0.2) b	6.7 (0.9) a	10.3 (0.5) a	19.5 (1.1) a	80 (4.0) b	2.32 (0.29) bc
CR+D	8.7 (0.6) b	6.8 (0.5) c	12.4 (1.9) b	15.5 (0.9) c	27.9 (2.9) b	90 (3.2) b	3.05 (0.25) c
				Pr > F			
	<0.0001	<0.0001	0.0002	<0.0001	0.0066	0.0003	0.0102

† NT, no tillage; D, disking; R+D, single-ripping plus disking; CR+D, cross-ripping plus disking.

‡ Predicted using a smaller subset of samples; sums of components are not compatible to this column.

§ Means within columns followed by the same letter are not different ($\alpha = 0.10$).

ated with FC, WC, and AWC. Soil strength was variable from season to season, although not directly comparable as different sampling methods were used. Soil strength in March 2016 exceeded 2500 kPa for most treatments, which is considered to be a limiting value for conifer roots (Blouin et al., 2008). Soil strength values were approaching this value on CR+D plots. In soil test pits, the lower soil strength at 70 to 90 cm was likely a result of the increased θ and finer soil texture at those depths. Conversely, the higher soil strength at 20 to 60 cm indicates that upper soil layers were likely the most impacted by site preparation equipment. Lower soil strength within planted tree rows may have partly been a result of the narrow furrow (~30 cm) created by the coulter wheel during machine planting. This furrow, or 'mini-rip', likely aided in the initial growth and establishment of seedlings in lower intensity treatments, whereas cross-ripping probably had a greater impact on the volume of soil within and around planted tree rows.

Soil plant relationships are directly influenced by soil pore size, shape, and distribution, which are considered important factors in determining soil gas-exchange and water movement (Sutton, 1991). Growth responses in loblolly pine by treatment were probably best explained by changes in ρ_b. The average ρ_b for NT was within the limiting plant growth range for sandy clay loams (1.55 to 1.70 Mg m^{-3}) (Daddow and Warrington, 1983). Foil and Ralston (1967) found a significant negative correlation between loblolly pine root growth and soil ρ_b; lower ρ_b resulted in higher root length and mass of pine seedlings across different soil textures. Studies assessing belowground development as a result of soil tillage are limited due to the difficulties associated with destructively harvesting roots, which can easily be under or overestimated (Schilling et al., 2004). Inferences based on our belowground data are limited since we did not measure different root size classes for pine seedlings. Additionally, soil strength and ρ_b were higher in less intensive tillage treatments. As a result, excavation procedures were more abrasive to the surrounding soil and it may be possible that root systems were inadvertently destroyed and/or under sampled.

One source of potential error in our study was that dozer ripping was treated operationally, and as a result, sampling did not explicitly account for within-plot variability due to proximity to ripper traces. This was probably more so the case with single-ripping versus cross-ripping, since the latter loosened the greatest volume of soil compared to other treatments. Loblolly pine trees growing in soils of lower ρ_b are capable of growing across a broader range of soil water contents (Siegel-Issem et al., 2005). After one growing season, it was likely that pine seedlings in cross-ripped soils were better able to handle abrupt and/or adverse changes in this mine soil environment compared to other treatments due to their greater root surface area. Despite significantly lower pine seedling survival, NT had above and belowground growth responses that were generally similar to tilled plots, with the exception of CR+D, which had the lowest overall soil strength and ρ_b. Soils exhibiting a lower mechanical impedance are more likely to increase the rate at which tree seedling roots begin to exploit soil outside of the planting furrow (Morris and Lowery, 1988).

Our findings are supported by similar research on mined land that found improvements in vegetative growth as a result of subsurface tillage (Ashby, 1996; Bauman et al., 2014; Burger and Evans, 2010; Dunker and Darmody, 2005). Additionally, the pine seedlings in our study responded favorably to soil tillage, similar to results from other mechanical site preparation studies involving loblolly pine (Carlson et al., 2006; Furtado et al., 2016; NCSFNC, 2000; Wheeler et al., 2002; Will et al., 2002). To account for the soil volume needed for tree roots, subsurface tillage is a recommended practice on compacted mine soils for the long-term growth and productivity of reclaimed forests (Sweigard et al., 2007). Short-term effects of combined surface and subsurface tillage have proven to be beneficial for loblolly pine seedling growth at this mine site.

CONCLUSIONS

Surface and subsurface soil tillage increased tree survival during the first growing season compared to NT. All levels of tillage resulted in higher cover of herbaceous species. After one growing season, the two ripped treatments had higher aboveground biomass production of herbaceous species compared to NT and D. First year growth and biomass production of pine seedlings were lowest on D, while intermediate levels were found on NT and R+D. Overall, the most intensive tillage treatment (CR+D) accrued the greatest SVI growth and total pine tree biomass production during the first growing season. This positive response was attributed to the significant improvements in soil physical properties on CR+D compared to NT (i.e., lower soil strength and ρ_b, higher total porosity). Without any form of tillage, an herbaceous cover crop would be difficult to establish on scraper placed mine soil based on our findings. Machine planting likely offset some short-term growth limitations of pine seedlings that would be expected from planting in compacted soil. Additional measurements are necessary to determine the evolution of mine soil physical properties in tilled versus no-tilled plots and how loblolly pine trees occupy the soil within these treatments over time.

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